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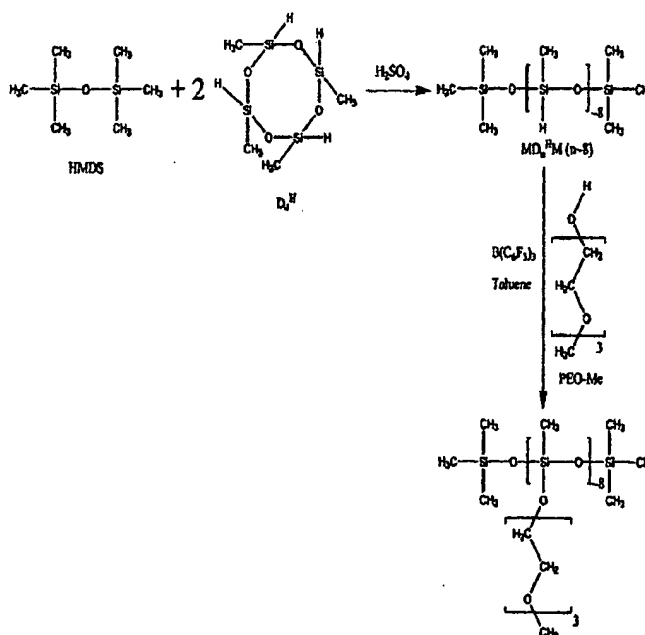
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[Continued on next page]

(54) Title: NONAQUEOUS LIQUID ELECTROLYTE



(57) Abstract: Disclosed is a nonaqueous liquid electrolyte comprising poly(siloxane-g-3 ethylene oxide) and its synthesis. This electrolyte provides significant safety, improved electrochemical stability, improved conductivity, lower impedance, and lower manufacturing costs.



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- *with amended claims*

**NONAQUEOUS LIQUID ELECTROLYTE****REFERENCE TO PRIOR FILED APPLICATIONS**

[0001] This application claims priority to copending provisional application serial number 60/451,065 entitled "Method for Fabricating Composite Electrodes" filed February 26, 2003; and to copending provisional application serial number 60/446,848 entitled "Polymer Electrolyte for Electrochemical Cell" filed February 11, 2002; and to copending provisional application serial number 60/443,892 entitled "Nonaqueous Liquid Electrolyte" filed January 30, 2003; and to PCT/US03/02127 filed January 22, 2003; and to PCT/US0302128 filed January 22, 2003; and is a Continuation-in-Part of co-pending application Serial Number 10/167,490 filed June 12, 2002, which is a Continuation-in-Part of co-pending application Serial Number 10/104,352, filed March 22, 2002, the disclosure of each of which is incorporated herein by reference.

**GOVERNMENT LICENSE RIGHTS**

[0002] This invention was made with United States Government support under NIST ATP Award No. 70NANB043022 awarded by the National Institute of Standards and Technology (NIST) and NSF 9810623. The United States Government has certain rights in this invention pursuant to NIST ATP Award No. 70NANB043022 and pursuant to Contract No. W-31-109-ENG-38 between the United States Government and the University of Chicago representing Argonne National Laboratory, and NIST 144 LM01, Subcontract No. AGT DTD 09/09/02, and NSF 9810623.

**TECHNICAL FIELD**

[0003] The present invention relates to electrochemical storage devices containing a nonaqueous polymer electrolyte with high ionic conductivity, low impedance, and high thermal stability. More particularly the present invention relates to polysiloxane type electrolytes for electrochemical storage devices.

**BACKGROUND**

[0004] The demand for lithium secondary batteries to meet high power and high-energy system applications has resulted in substantial research and development activities to improve their safety, as well as performance. As the world becomes increasingly dependent on portable electronic devices, and looks toward increased use of electrochemical storage devices for vehicles, power distribution load leveling and the like, it is increasingly important that the safety of such devices be paramount, especially as these devices are being used in such environments as airliners and space vehicles. The effort to date has included research in flame-retardants, solid polymer electrolytes, and new electrolyte concepts with improved thermostability. Thus, the development of highly conductive electrolytes, free of any problems associated with volatile and combustible solvents, is of paramount importance.

Polymer electrolytes have a number of advantages over the materials currently used in high-performance batteries. Compared to conventional batteries using heavy metals such as lead, nickel, and cadmium, the lithium-based polymer electrolyte batteries would be many times lighter. The proposed designs of these batteries would also allow them to be formed into various shapes besides the traditional cylindrical or rectangular shapes typical in regular batteries. (See, Gray, F. M. *Solid Polymer Electrolytes*; VCH Publishers: New York, 1991, at 1-4, 5-21). These advantages have fueled commercial interests and research interests into improving the conductive properties of polymer electrolytes. Poly(ethylene oxide) (PEO) has been known to dissolve alkali metal salts and exhibit conductivity since the early 1970's. (See, Fenton, D. E. ; Parker, J. M.; Wright, P. V. *Polymer* 1973, 14, at 589). The properties of PEO have been studied extensively and are outlined in a number of review articles and texts. (See Gray *supra*; See also, Shriver, D. F.; Bruce, P. G. in *Solid State Electrochemistry*, P. G. Bruce, ed., Cambridge University Press: New York, 1995, at 95, 97-106). Of more recent interest has been a class of polymers with Si-O backbones known as polysiloxanes.

(See, Mark, J. E.; Allcock, H. R.; West, R. *Inorganic Polymers*; Prentice Hall: New Jersey, 1992, at 3). The Si-O backbone of these polymers is highly flexible, yet retains its chemical and thermal integrity. Polysiloxanes also have low glass transition temperatures,  $T_g$ , and, when substituted with oligoethylene oxide groups, solvate lithium salts, making the polysiloxanes good candidates for potentially useful polymer electrolytes. (See, Hooper, R.; Lyons, L. J.; Mapes, M. K.; Schumacher, D.; Moline, D. A.; West, R. *Macromolecules* 2001, 34, 931. R. Hooper, L. J. Lyons, D. A. Moline, R. West, *Silicon Chemistry* 2002, 1, at 121; Lin, C.; Kao, H.; Wu, R.; Kuo, P. *Macromolecules* 2002, 35, at 3083; Zhou, G.; Khan, I. M.; Smid, J. *Macromolecules* 1993, 26, at 2202; Siska, D. P.; Shriver, D. F. *Chem. Mater* 2001, 13, at 4698; Zhu, Z.; Einset, A.G.; Yang, C.; Chen, W.; Wnek, G. E. Zhu, Z.; Einset, A.G.; Yang, C.; Chen, W.; Wnek, G. E. *Macromolecules* 1994, 27, at 4076; Zhu, Z.; Einset, A.G.; Yang, C.; Chen, W.; Wnek, G. E.; Fish, D.; Khan, I.M.; Wu, E.; Smid, J. *British Polymer Journal* 1988, 20, at 286; Morales, E.; Acosta, J.L. *Electrochimica Acta* 1999, 45, at 1049.)

[0005] The present inventors synthesized the polysiloxane polymers of the present invention with the goal of creating low viscosity, low molecular weight samples to enhance ionic conductivity.

[0006] A primary objective of the present invention is to provide a high conductivity, safe liquid electrolyte for use in electrochemical storage devices, especially lithium secondary batteries, as well as super capacitors and hybrid devices.

[0007] Another objective is to provide a safe electrolyte that is easy and inexpensive to manufacture.

[0008] Yet another objective is to provide an electrolyte for medical and high energy applications.

**SUMMARY**

[0009] Accordingly, the present invention relates to electrochemical storage devices, especially lithium-based secondary batteries, with a nonaqueous and nonvolatile polymeric electrolyte with high room temperature ionic conductivity and enhanced safety.

[0010] To fulfill the above objectives, the nonaqueous and nonvolatile polymeric electrolyte solutions in the present invention are prepared by using the compositions which comprise poly(siloxane-g-ethylene oxide) in a liquid state with proper viscosity and a dissolved lithium salt.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0011] Fig. 1 is a visual summary of the synthesis of poly(siloxane-g-3 ethylene oxide) (n~8), (Sample W100).

[0012] Fig. 2 is a plot of conductivity derived from impedance measurements for several side chain oxygen to lithium (EO:Li) ratios.

[0013] Fig. 3 is a plot of potential vs. current density for Sample W100 Doped with LiTFSI (EO:Li = 32:1).

[0014] Figs. 4A and 4B represent the structures of the three linear polysiloxane polymers of Example 2.

[0015] Fig. 5 is a plot of conductivity derived from impedance measurements of the samples of Example 2.

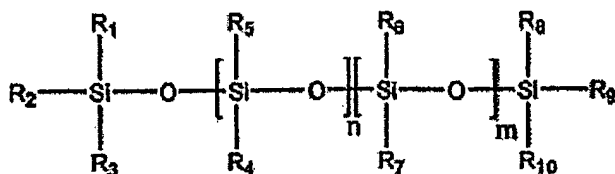
**DETAILED DESCRIPTION**

[0016] Poly(siloxane-g-ethylene oxide) (see General Formula I below) electrolyte shows outstanding flame resistance. Its propagation rate is significantly lower than conventional liquid electrolyte for lithium ion batteries and low molecular weight polyethylene oxide electrolyte. This is because the inorganic siloxane backbone naturally acts as a combustion inhibitor, resulting in a two stage combustion process. The initial stage involves

decomposition of the stable polymer into flammable volatile by-products. For polysiloxanes such as our electrolyte, this requires a lot of energy due to the strength of the Si-O backbone. This means that in order for combustion to occur, the heat added must be sufficient to decompose the polymer, ignite the by-products, and transfer enough heat back to the polymer to sustain the reaction. Additionally, our polymer is more thermally stable than the carbonates presently used in the industry as a standard. This stability arises from the polymer's large molecular size, nonvolatile nature and the higher temperatures required to vaporize. The Si-O backbone also gives this polymer the added benefit of being nontoxic. The thermal stability and nontoxicity of this polymer electrolyte make it particularly well suited for medical device applications, especially implanted batteries for such devices as cardiac assist pumps, insulin pumps, neuromuscular stimulators, cardiac pacemakers, automatic defibrillators, cochlear implants, and other bioelectronic devices. The usage of this polymer in place of the traditional carbonates in medical device batteries would substantially improve safety. The polymer electrolyte of the present invention is also well suited for high energy applications such as electric and hybrid vehicles, submarines, satellites, and load-leveling installations.

**[0017] EXAMPLE 1**

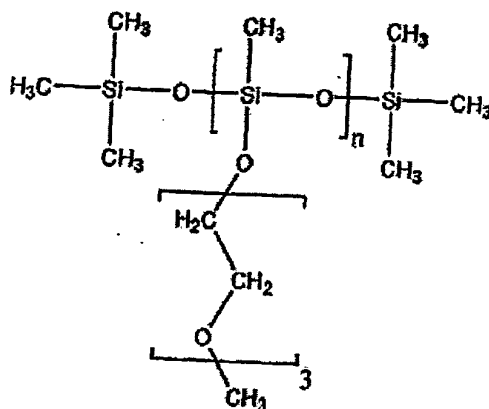
[0018] Referring to Fig. 1, a visual summary of the synthesis, the liquid polymer electrolyte of the form visually depicted by General Formula I was synthesized.



### General Formula I

[0019] In particular, a species of this type with ( $n=8$  and  $m=0$ ), labeled W100 poly(siloxane-g-3 ethylene oxide) ( $n=8$ ) (General Formula II) was synthesized using

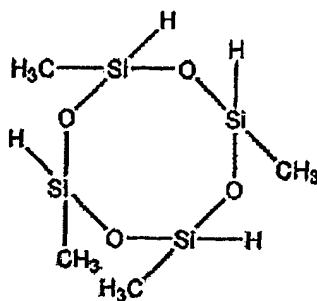
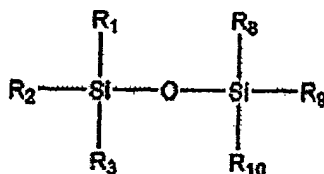
commercially available precursors involved in two major steps, as described below. Note R4 is  $[-O-(\text{alkylene oxide})_k-R11]$  wherein R11 is alkyl group. Note further that viscosity increases with n, becoming a solid at values exceeding about 20. Preferably, n should range from 4 to 20, more preferably from 4 to 12, and most preferably approximately 8. R1, R2, R3, R8, R9 and R10 are preferably chosen from the group consisting of: methyl, ethyl, propyl, and butyl. R5, R6 and R7 are preferably chosen from the group consisting of: methyl, ethyl, propyl, and butyl.



General Formula II

[0020] Step 1: Ring Opening Polymerization Synthesizing a  $MD_n^H M$  ( $n \sim 8$ ) Intermediary

[0021] The commercially available compounds 1,3,5,7-tetramethylcyclotetrasiloxane ( $D_4^H$ , Gelest Inc., 68.59 g or 0.286 mol) (General Formula III) and hexamethyldisiloxane (HMDS, Aldrich, 23.15 g or 0.143 mol) (a disiloxane described by General Formula IV for the case wherein,  $R1 = R2 = R3 = R8 = R9 = R10 = CH_3$ ) were used as precursor materials.

General Formula III: Chemical Structure of D<sub>4</sub><sup>H</sup>

General Formula IV: Chemical Structure of Disiloxane

[0022] Note that alternate precursor materials may be used such as cyclical polysiloxane with three to ten silicon-oxygen repeating units, for example:

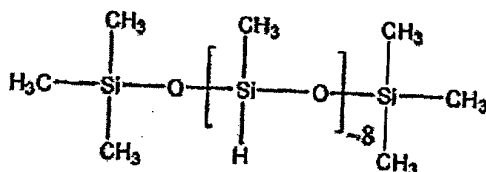
- D<sub>3</sub><sup>H</sup>: 1,3,5-trimethylcyclotrisiloxane,
- D<sub>4</sub><sup>H</sup>: 1,3,5,7-tetramethylcyclotetrasiloxane (as used in Example 1),
- D<sub>5</sub><sup>H</sup>: 1,3,5,7,9-pentamethylcyclopentasiloxane,
- D<sub>6</sub><sup>H</sup>: 1,3,5,7,9,11-hexamethylcyclohexasiloxane,
- D<sub>7</sub><sup>H</sup>: 1,3,5,7,9,11,13-heptamethylcycloheptasiloxane,
- D<sub>8</sub><sup>H</sup>: 1,3,5,7,9,11,13,15-octamethylcyclooctasiloxane,
- D<sub>9</sub><sup>H</sup>: 1,3,5,7,9,11,13,15,17-nonamethylcyclononasiloxane, or
- D<sub>10</sub><sup>H</sup>: 1,3,5,7,9,11,13,15,17,19-decamethylcyclodecasiloxane.

Preferred is from about three to about five silicon-oxygen repeating units.

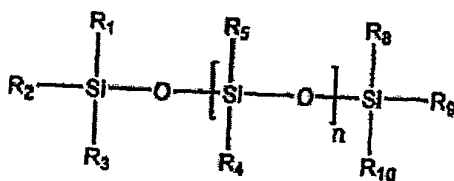
[0023] A ring opening polymerization of the cyclic compound was performed through the addition of a chain-stopping compound, HMDS (in a 1:2 molar ratio), in the presence of concentrated sulfuric acid (2.6% by wt, Fisher Scientific, 1.85 g) and stirred at 60°C for 24 hours. The 1:2 ratio was used in this preferred example; however, the ratio is not limited

to 1:2. Preferably, the chain-stopping compound is added in an amount sufficient to limit final chain lengths to  $n=4$  to 20. For example, if the ratio is  $2 D_4^H : 1$  disiloxane,  $n$  will be  $\sim 8$ ; for  $3 D_4^H : 1$  disiloxane,  $n$  will be  $\sim 12$ ; etc.

[0024] The resulting mixture was then allowed to return to room temperature and washed with 10%  $NaHCO_3$  (3 x 15 ml) and deionized water (6 x 10 ml). This liquid was dissolved in diethyl ether (200 ml) and then dried over  $Na_2SO_4$ . The diethyl ether solvent was removed on a rotary evaporator. The sample was then again dried at  $70^\circ C$  under vacuum (0.05 torr) overnight (about 16 hours). At this step Nuclear Magnetic Resonance (NMR) characterization was performed on the current product,  $MD_n^H M$  ( $n \sim 8$ ) (General Formula V, with a more generalized chemical structure of the Intermediary shown in General Formula VI), yielding a spectrum consistent with the proposed structure (Table 2).  $R_1$ ,  $R_2$ ,  $R_3$ ,  $R_8$ ,  $R_9$  and  $R_{10}$  are preferably chosen from the group consisting of: methyl, ethyl, propyl, and butyl.  $R_5$ ,  $R_6$  and  $R_7$  are preferably chosen from the group consisting of: methyl, ethyl, propyl and butyl.



General Formula V: Chemical Structure of  $MD_n^H M$  ( $n \sim 8$ )



wherein at least  $R_4$  or  $R_5$  is H.

General Formula VI: Generalized Chemical Structure of Intermediary

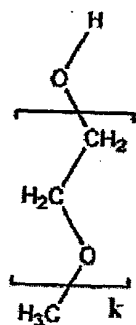
| NMR Spectra (in CDCl <sub>3</sub> ) | Line 1 (ppm)                                       | Line 2 (ppm)                                  |
|-------------------------------------|--|---|
| <sup>1</sup> H                      | 4.70<br>(broad, 1H, Si-H)                          | 0.21 ~ 0.12<br>(m, 5.3H, Si-CH <sub>3</sub> ) |
| <sup>29</sup> Si                    | 9.55<br>(m, O-Si(CH <sub>3</sub> ) <sub>3</sub> ), | -35.17<br>(Si-H)                              |

Table 2: NMR Spectra of MD<sub>n</sub><sup>H</sup>M (n~8)

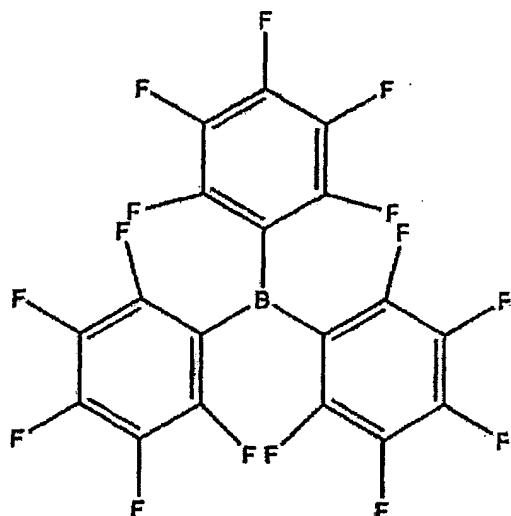
## [0025] Step 2: Addition of a PEO Side-chain

The above sample MD<sub>n</sub><sup>H</sup>M (n~8) (48.54 g, 0.617 mol Si-H) was then mixed in a 500 ml flame dried flask containing tri(ethyleneglycol) monomethyl ether (PEO-Me) (k=3) (Aldrich, 101.22 g or 0.617 mol) (described by the General Formula VII for the case wherein k=3). Also added to the mixture was tris(pentafluorophenyl)boron, B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub>, (Aldrich, 0.16 g or 0.31 mmol) (General Formula VIII), which served as a catalyst for the dehydrocoupling reaction which occurs between the Si-H groups of the MD<sub>n</sub><sup>H</sup>M (n~8) and the O-H groups of the PEO-Me (m=3). Note, the dehydrocoupling catalyst should be loaded as a percentage of the moles of Si-H groups present in the substrates, preferably between 0.01% and 10%, more preferably between 0.01% and 2.00%, and most preferably about 0.05% on a per mole basis. This mixture was vacuum pumped down (~0.05 torr) and then filled with argon, four times in succession. Next, a solvent (150 mL toluene, dried over sodium) was added and the entire mixture was heated to 70-75°C, which caused bubbling to occur. Other solvents such as benzene may be used in place of toluene, and the mixture may be heated to between 40°C and 200°C. The mix was then stirred until this bubbling ceased, approximately 17 hours. The sample was then further dried at 125°C under vacuum (0.02 torr) to generate a colorless oil (137.6 g). Infrared spectroscopy (IR) showed the absence of H-O or Si-H groups, an indication that our reaction proceeded to completion. Table 3 shows the spectra resulting from the NMR, similarly indicative of the absence of H-O or Si-H groups, and that the

reaction proceeded to completion (Table 3). Detecting traces of boron via mass spectroscopy, FTIR, X-ray diffraction, and/or neutron diffraction in a polysiloxane, and in particular in poly(siloxane-g-3 ethylene oxide) (n~8), could be used to reveal that our inventive employment of a boron catalyst was utilized. It is noted that, although boron is considered the best catalyst, alternate catalysts including alkali metal or alkaline earth hydroxides, alkali metal or alkaline earth carbonates, triethylamine, and pyridine may be used. *See*, S. Kohama, Y Umeki, J., Applied Polymer Sci., 21, 863 (1977). For example, and without limitation, zinc octanoate, triethylamine, pyridine, potassium hydroxide, magnesium hydroxide, potassium carbonate may be used. Experiments have further demonstrated that a rhodium complex,  $\text{RhCl}(\text{PPh}_3)_3$ , is an efficient catalyst but produces a dark color in the polymer which is difficult to remove.



General Formula VII: Chemical Structure of PEO-Me

General Formula VIII: Chemical Structure of  $B(C_6F_5)_3$ 

| NMR Spectra (in $CDCl_3$ ) | Line 1 (ppm)                   | Line 2 (ppm)              | Line 3 (ppm)                        |
|----------------------------|--------------------------------|---------------------------|-------------------------------------|
| $^1H$                      | 3.70~3.30<br>(m, 12H, $CH_2$ ) | 3.15<br>(s, 3H, $OCH_3$ ) | 0.05~0.10<br>(m, 5.1H, Si- $CH_3$ ) |

Table 3: NMR Spectra of Sample W100

**[0026] Properties**

**[0027] Ionic Conductivity:** When doped, Sample W100, by virtue of its low molecular weight and viscosity, displays high levels of ionic conductivity. The sample was initially dried on a high vacuum line (pressure reached  $9.5 \times 10^{-5}$  torr) following synthesis. Before testing the samples were doped with the lithium salt,  $LiN(SO_2CF_3)_2$  (LiTFSI) at various concentrations. These concentrations were calculated based on the molar ratios between the amount of side-chain oxygen molecules in the sample and lithium cations present in the salt (Table 4). Alternate candidate alkali metal salts include the lithium salts:  $LiClO_4$ ,  $LiBF_4$ ,  $LiAsF_6$ ,  $LiPF_6$ ,  $LiCF_3SO_3$ ,  $Li(CF_3SO_2)_2N$ ,  $LiC(CF_3SO_2)_3$ ,  $LiN(SO_2C_2F_5)_2$ , lithium bis(oxalato) borate ("LiBOB"), lithium alkyl fluorophosphates, and mixtures thereof. Other alkali metal salts may be used, particularly those comprising at least one quaternary

ammonium salt having an anion selected from the following groups:  $\text{ClO}_4^-$ ,  $\text{BF}_4^-$ ,  $\text{AsF}_6^-$ ,  $\text{PF}_6^-$ ,  $\text{CF}_3\text{SO}_3^-$ ,  $(\text{CF}_3\text{SO}_2)_2\text{N}^-$ ,  $\text{C}(\text{CF}_3\text{SO}_2)_3\text{C}^-$ ,  $(\text{C}_2\text{F}_5\text{SO}_2)_2\text{N}^-$ ,  $\text{PF}_3(\text{C}_2\text{F}_5)_3^-$ ,  $\text{PF}_3(\text{CF}_3)_3^-$  and  $\text{B}(\text{C}_2\text{O}_4)_2^-$ .

| EO:Li  | Sample W100 (g) | LiTFSI (g) |
|--------|-----------------|------------|
| 24.1:1 | 1.58            | 0.24       |
| 15.1:1 | 1.49            | 0.37       |

Table 4: LiTFSI Doping of Sample W100

[0028] This doping was achieved through one of two methods. The first involves direct doping of the salt and polymer by placing them in a Nalgene cup in an argon atmosphere dry box. Once inside the box the mixture was placed in a drying tube containing a Teflon stir bar. Next the tube was removed from the dry box and placed on a Schlenk line to enable the sample and salt to mix under an argon flow until homogenous mixing occurred. The criterion used to evaluate this level of mixing was the absence of salt crystals based on unaided visual inspections. This was achieved following several hours (overnight) of constant stirring. The second, or solution, method involves placing the desired amount of sample in a Nalgene cup that is then transferred to a sealed drying tube with a Teflon stir bar within the dry box. The salt is transferred into the tube through a syringe containing 0.052 M LiTFSI in a tetrahydrofuran (THF) solution under an argon flow. The mix was then allowed to stir to achieve homogeneity on a Schlenk line. The THF solvent is removed on the Schlenk line and the tube is then placed on a high vacuum line until a pressure below  $3 \times 10^{-5}$  torr is reached. The direct doping method was used in the preparation of doped Sample W100.

[0029] The solution doping method was used when less than 15 mg of salt will be used since that small amount of salt cannot be measured precisely in a dry box. When using 50 to 100 mg of salt, precise amounts can be measured in a dry box allowing the use of the direct method, which does not expose the sample to additional solvent (which then needs to be removed). Sample W100 was mixed with the direct method since about 100 mg of salt was

added to the pure polymers. It is quicker and ensures that no additional solvent needs to be used.

[0030] Sandwich conductivity cells sealed with o-rings were used to measure conductivity. The cells were placed in the dry box and had their dimensions measured to

enable the calculation of conductivity according to the equation,  $\sigma = \frac{L}{RA}$ , where  $\sigma$  is conductivity (S/cm), L is the length of the containment ring (cm), R is the resistance ( $\Omega$ ) and A is area (cm<sup>2</sup>). Three (3) different containment rings were used on our cells, giving

geometric factors ( $\frac{L}{A}$ ) between 0.208 and 0.293 cm<sup>-1</sup>. Resistance was derived from impedance measurements according to the following equation,  $R = Z \times \cos(\theta)$ , where Z is impedance ( $\Omega$ ) and  $\theta$  corresponds to the phase angle. These values were measured by a Princeton Applied Research Potentiostat/Galvanostat Model 273A with a Model 1025 Frequency Response Analyzer using PAR PowerSine software. The parameters for these tests were a frequency range of between 75.0 Hz and 100 kHz and a default AC amplitude of 10 mV. Variations in temperature were achieved using a condenser connected to a Brinkman MGW Lauda RM 6 circulating bath.

[0031] Fig. 2 shows the results of impedance measurements yielding conductivity calculations, which were recorded at various temperatures and plotted. It is apparent that an EO:Li ratio of 15:1 yields the best conductivity for our Sample W100. This data was then fit

to the Vogel-Tamman-Fulcher (VTF) equation,  $\sigma = AT^{-1/2} \exp\left[\frac{-B}{T-T_0}\right]$ , where A ( $\frac{SK^{1/2}}{cm}$ ) and B (K-1) are constants and T<sub>0</sub> (K) is the ideal glass transition temperature. The equation parameter B, is related to activation energy (E<sub>a</sub>) by a constant such that,

$$E_a = B \times (8.31 \frac{J}{molK}) \quad (\text{Table 5}).$$

| EO:Li  | $\sigma$ @ 25°C<br>(S/cm) | $\sigma$ @ 37°C<br>(S/cm) | $E_a$<br>(kJ/mol) | $T_o$<br>(K) |
|--------|---------------------------|---------------------------|-------------------|--------------|
| 24.8:1 | $2.01E^{-4}$              | $3.08E^{-4}$              | 3.07              | 202          |
| 15.1:1 | $2.66E^{-4}$              | $4.58E^{-4}$              | 4.37              | 196          |

Table 5: Conductivity Data for Sample W100

[0032] Table 6 summarizes the conductivity measurements and VTF derived data for both the 24.8:1 and 15:1 EO:Li doping ratios. The values of temperature and conductivity are presented in the forms of  $1/T \times 1000$  and  $\log \sigma$ , respectively, so that the data can be easily plotted (as in Figs. 2 and 6) and related to the VTF equation. The corresponding calculated  $\log \sigma$  values derived from the VTF fit are also presented for data point for comparison.

| 24.8:1            |               |                 | 15:1              |               |                 |
|-------------------|---------------|-----------------|-------------------|---------------|-----------------|
| Experimental Data |               | Calculated Data | Experimental Data |               | Calculated Data |
| $1/T \times 1000$ | $\log \sigma$ | VTF fit         | $1/T \times 1000$ | $\log \sigma$ | VTF fit         |
| 3.5430            | -4.0117       | -4.0231         | 3.5581            | -4.0268       | -4.0289         |
| 3.4680            | -3.8781       | -3.8821         | 3.4620            | -3.7992       | -3.8035         |
| 3.3495            | -3.6963       | -3.6861         | 3.3518            | -3.5746       | -3.5754         |
| 3.2263            | -3.5113       | -3.5108         | 3.2191            | -3.3382       | -3.3361         |
| 3.1158            | -3.3744       | -3.3735         | 3.1099            | -3.1659       | -3.1633         |
| 3.0225            | -3.2651       | -3.2700         | 2.9936            | -2.9947       | -2.9986         |
| 2.9382            | -3.1868       | -3.1846         | 2.9235            | -2.9097       | -2.9081         |

Table 6: Conductivity Measurements and VTF Derived Data

[0033] Electrochemical Stability. For the measurement of the electrochemical stability window of the polymer electrolyte, stainless steel type 2032 button cell assemblies were used, with a stainless steel disc as a working electrode and a lithium metal disc as a counter electrode. The measurement cell was assembled in an argon-filled dry box.

[0034] Fig. 3 shows the electrochemical stability of the polymer electrolyte measured by using ZAHNER electrochemical workstation IM6 with scan rate of 5 mV/sec from 2.8 V to 6.0 V measured at 25°C. The first scan cycle displays small current increase from 4.0 V

onward. Successive scans show that Sample W100 doped with LiTFSI can be cycled up to 4.5 V without an additional decomposition.

[0035] Viscosity ( $\eta$ ): The viscosity of Sample W100 (see Table 7) was measured by using a Brookfield type viscometer (DV-II+) with a spindle speed of 50 RPM measured at 25°C.

| Temp (C) | EO:Li | $\eta$ (cPs) |
|----------|-------|--------------|
| 25.0     | 32:1  | 26.50        |

Table 7

[0036] **EXAMPLE 2**

[0037] To further explore the properties of related polymer electrolytes, the three linear polysiloxane polymers shown in Figs. 4A and 4B were synthesized. The liquid samples were doped with LiTFSI at various concentrations before measuring conductivity. A previous study found the 32:1 EO:Li ratio to be the optimum ratio for maximum conductivity, but the polymers examined in that study were double-comb polysiloxanes. (*See, Hooper, supra.*)

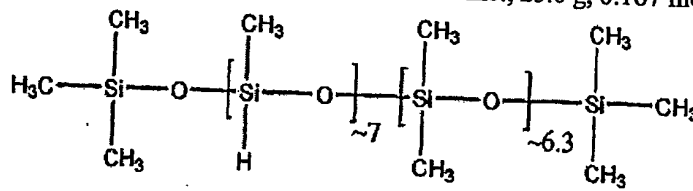
[0038] Past studies have measured conductivities that could be considered commercially viable (*Ibid.*), but the polysiloxanes that were studied had to be meticulously synthesized at the laboratory level. Trying to convert these syntheses to commercial volumes would likely prove to be too difficult and costly. Thus, the methyl polysiloxane samples have the advantage of having been synthesized by much simpler schemes from the readily available starting materials poly(methylhydrosiloxane), PMHS, and poly(ethylene glycol), PEO, as a step toward making the transition from laboratory to market.

[0039] For comparison purposes, the liquid polymers W22P, W76, W100, and W102 were synthesized at the Organosilicon Research Center at the University of Wisconsin-Madison. The liquid samples were dried on a high vacuum line until ultimate pressure was

reached (W22P,  $1.5 \times 10^{-5}$  torr; W76,  $2.2 \times 10^{-5}$  torr; W100,  $9.5 \times 10^{-5}$  torr; W102,  $9.5 \times 10^{-5}$  torr).

[0040] Specifically, and by way of example, Sample W76 (Fig. 4A) was synthesized in the same way as W100 except omitting Step 1 ("Ring Opening Polymerization Synthesizing a  $\text{MD}_n^{\text{H}}\text{M}$  ( $n \sim 8$ ) Intermediary") above. The materials used were:

55%PMHS-co-PDMS ( $M_w = 900 \sim 1200$  from Gelest Inc., 25.0 g, 0.167 mol Si-H)



Tri(ethyleneglycol) monomethyl ether (Aldrich, 27.38 g, 0.167 mol);

$\text{B}(\text{C}_6\text{F}_5)_3$  (Aldrich, 0.77 g, 1.5 mmol);

Toluene (150 ml).

[0041] Sample W76 (27 g) was thus obtained and tested. Spectra data (IR, NMR) for W76 were similar to that for W100 except for the presence of an additional absorption band at  $-19 \sim -22$  ppm on the  $^{29}\text{Si}$  NMR spectrum. Sample W76, where the PEO side chains are attached to the siloxane backbone through Si-O bonds, is a novel material for use as an electrolyte. (Note that in terms of General Formula I, the precursor for Sample W76,  $n \sim 7$  and  $m \sim 6.3$ . Generally, in the present invention,  $m$  may range from 0 to about 20, or more preferably from 0 to about 8, and most preferably should be about 0).

[0042] Similarly, Sample W102 (Fig. 4B) was synthesized according to Step 2 in the Sample W100 preparation above (i.e., omitting step 1). The materials used were:

PMHS ( $n \sim 34$ ) (Gelest Inc., 41.59 g, 0.638 mol Si-H);

Tri(ethyleneglycol) monomethyl ether (Aldrich, 104.59 g, 0.638 mol);

$\text{B}(\text{C}_6\text{F}_5)_3$  (Aldrich, 0.17 g, 0.33 mmol);

Toluene (220 ml)

[0043] Sample W102 (139.3 g) was thus obtained and tested. Spectra (IR, NMR) data for W102 were similar to W100.

[0044] Referring to Fig. 4B, it may be seen that Sample 22P is almost identical to Sample W102. The difference in the length of the silicon oxide backbone results from the use of potassium carbonate ( $K_2CO_3$ ) as a catalyst in formulating Sample W22P versus the use of tris(pentafluorophenyl)boron ( $B(C_6F_5)_3$ ) as a catalyst in formulating Sample W102. Importantly, the boron-containing catalyst results in more precise control of the length of the silicon oxide backbone, and a significant improvement in performance. The use of a boron-containing catalyst is therefore much preferred to other catalysts.

[0045] Viscosity ( $\eta$ ): The viscosity of Samples W22P, W76, and W102 (see Table 8) was measured using the same method as Sample W100 (using a Brookfield type viscometer (DV-II+) with a spindle speed of 50 RPM measured at 25°C.).

| Sample | Temp (C) | EO:Li | $\eta$ (cPs) |
|--------|----------|-------|--------------|
| W22P   | 25°C     | 32:1  | 96.00        |
| W76    | 25°C     | 32:1  | 113.20       |
| W102   | 25°C     | 32:1  | 64.13        |

Table 8

[0046] Polymer Electrolyte Preparation.

[0047] Doped polymer samples were prepared by direct mixing of the salt with the polymer. Both polymer and the calculated amount of salt (side-chain oxygen to lithium ion ratio) were placed in a Nalgene cup in the dry box and sealed in a custom drying tube with a stir bar. Once out of the dry box, the tube was placed on a Schlenk line to allow the polymer and salt to stir under an argon flow until a homogeneous mixture was achieved.

[0048] Fig. 5 is a plot of conductivity derived from impedance measurements of the samples of Example 2. O-ring sealed sandwich conductivity cells were loaded in the dry box of each sample using one of three containment rings. The geometric factor,  $l/A$ , for the rings ranged from 0.208 to 0.293  $cm^{-1}$ . Ionic conductivities were calculated with the equation

$s = 1 / R * 1 / A$ , where  $s$  is conductivity and  $R$  is resistance. Resistance was calculated from the impedance ( $Z$ ) using the equation,  $R = Z * \cos(q)$  where  $q$  is the phase angle and  $Z$  is the impedance. The impedance was measured on a Princeton Applied Research Potentiostat/Galvanostat Model 273A with a Model 1025 Frequency Response Analyzer operated under computer control using PAR PowerSine software. The frequency ranged from 75.0 Hz to 100 kHz and the default AC amplitude of 10 mV was used for each measurement. Measurements were taken at temperatures ranging from 0 to 70°C by placing the conductivity cell inside a condenser attached to a Brinkman MGW Lauda RM 6 variable temperature, circulating bath. Conductivity was calculated from the impedance measurements and plotted with respect to temperature. The plot of Fig. 5 was fit to the VTF equation, (See, Fulcher, G. S. J. Am. Ceram. Soc. 1925, 8, 339) in order to calculate the activation energy from the equation parameters. The samples W100 (tested at EO:Li doping ratios of 15:1 and 24.8:1) and W102 (tested at a EO:Li doping ratio of 24.8:1) outperformed the other samples tested. It is anticipated that W102 would also perform well at the 15:1 level. From Fig. 5, there appears to be a trend over all samples that there is an optimum EO:Li doping ratio range of about 5:1 to 50:1, more preferably about 12:1 to 28:1, even more preferably about 15:1 to 25:1, and most preferably about 15:1.

[0049] Fig. 6 is a plot of VTF derived conductivity for various concentrations of LiTFSI. It is evident that the sample W100 doped at 15:1 outperforms all other samples tested throughout the test range. It should be apparent that the present invention solves the long-felt need to create safe, high energy, lightweight electrochemical storage devices having liquid electrolytes. Batteries containing the present electrolyte would be inherently safer than those with more volatile, flammable, and unstable electrolytes, and have significantly better performance due to the lower impedance and increased conductivity. Additionally, the cost

of manufacturing the electrolyte of the present invention is anticipated to be lower than other alternate electrolytes.

[0050] **EXAMPLE 3**

[0051] Following the same synthetic procedures as in Example 1, but varying the amount of starting materials, Sample W119 was synthesized.

[0052] Step 1: Ring Opening Polymerization Synthesizing a  $MD_n^H M$  ( $n=4$ )

[0053] Commercially available Hexamethyldisiloxane HMDS (Aldrich, 41.44 g or 0.255 mol), 1,3,5,7-tetramethylcyclotetrasiloxane  $D_4^H$  (Gelest Inc., 61.24 g or 0.255 mol) (General Formula III), and concentrated sulfuric acid  $H_2SO_4$  (Fisher Scientific, 2.46 g) were used as precursors for the product  $MD_n^H M$  ( $n=4$ ) (78 g).

[0054] NMR analysis showed the following data:  $^1H$  NMR (in  $CDCl_3$ ): 4.70 ppm (broad, 1H, Si-H), 0.21 ppm~0.12 ppm (m, 7.4H, Si- $CH_3$ ).  $^{29}Si$  NMR (in  $CDCl_3$ ): 8.78ppm (m,  $OSi(CH_3)_3$ ), -36.54 ppm (m, Si-H).

[0055] Step 2: Addition of PEO side chains

[0056] Tri(ethyleneglycol) monomethyl ether (Aldrich, 65.85 g, 0.402 mol),  $MD_n^H M$  ( $n=4$ ) (40.39 g, 0.402 mol Si-H), Tris(pentafluorophenyl)boron  $B(C_6F_5)_3$  (Aldrich, 0.104 g, 0.202 mmol) were used to afford the colorless liquid product designated Sample W119 (96.7 g). Referring to General Formula II (as well as the final product in Fig. 1),  $n=4$ .

[0057] Spectroscopic Data: IR showed no HO groups (at 3300~3500  $cm^{-1}$ ) and no Si-H (at 2160  $cm^{-1}$ ) present.  $^1H$  NMR (in  $CDCl_3$ ): 3.70~3.30 ppm (m, 12H,  $CH_2$ ), 3.15 ppm (s, 3H,  $OCH_3$ ), 0.05~0.10 ppm (m, 7.4 H, Si- $CH_3$ ).

[0058] Viscosity was measured at 30.00 cPs.

[0059] Conductivity was measured at  $2.10 \times 10^{-4} Scm^{-1}$  at 25.1°C (at doping level of O/Li=24, using LiTFSI).

**[0060] EXAMPLE 4**

[0061] Following the same synthetic procedures as in Example 1, but varying the amount of starting materials, Sample W168 ( $n \approx 6$ ) was synthesized.

[0062] Step 1: Ring Opening Polymerization Synthesizing a  $MD_n^H M$  ( $n \approx 6$ )

[0063] Commercially available Hexamethyldisiloxane HMDS (Aldrich, 19.59 g, 0.121 mol), 1,3,5,7-tetramethylcyclotetrasiloxane  $D_4^H$  (Gelest Inc., 43.42 g, 0.181 mol), and concentrated sulfuric acid  $H_2SO_4$  (Fisher Scientific, 1.59 g) were used as precursors for the product  $MD_n^H M$  ( $n \approx 6$ ) (46.5 g).

[0064] NMR analysis yielded the following data:  $^1H$  NMR (in  $CDCl_3$ ): 4.70 ppm (broad, 1H, Si-H), 0.21 ppm–0.12 ppm (m, 6.1 H, Si- $CH_3$ ).  $^{29}Si$  NMR (in  $CDCl_3$ ): 8.92 ppm (m,  $OSi(CH_3)_3$ ), -36.72 ppm (m, Si-H).

[0065] Step 2: Addition of PEO side chains

[0066] Tri(ethyleneglycol) monomethyl ether (Aldrich, 39.72 g, 0.242 mol),  $MD_n^H M$  ( $n \approx 6$ ) (21.56 g, 0.243 mol Si-H), and Tris(pentafluorophenyl)boron  $B(C_6F_5)_3$  (Aldrich, 0.150 g, 0.293 mmol) were used to afford the colorless liquid product designated Sample W168 (59.0 g). Referring to General formula II (as well as the final product in Fig. 1),  $n \approx 6$ .

[0067] Spectroscopic Data: IR showed no HO groups (at 3300–3500  $cm^{-1}$ ) and no Si-H (at 2160  $cm^{-1}$ ) present.  $^1H$  NMR (in  $CDCl_3$ ): 3.70–3.30 ppm (m, 12H,  $CH_2$ ), 3.15 ppm (s, 3H,  $OCH_3$ ), 0.05–0.10 ppm (m, 5.9 H, Si- $CH_3$ ).

**[0068] EXAMPLE 5**

[0069] Following the same synthetic procedures as in Example 1, but varying the amount of starting materials, Sample W169 ( $n \approx 11$ ) was synthesized.

[0070] Step 1: Ring Opening Polymerization Synthesizing a  $MD_n^H M$  ( $n \approx 11$ )

[0071] Commercially available Hexamethyldisiloxane HMDS (Aldrich, 8.28 g, 0.051 mol), 1,3,5,7-tetramethylcyclotetrasiloxane  $D_4^H$  (Gelest Inc., 42.84 g, 0.179 mol), and

concentrated sulfuric acid  $\text{H}_2\text{SO}_4$  (Fisher Scientific, 1.58 g) were reacted at  $75^\circ\text{C}$  for 72 hours to afford the product  $\text{MD}_n^{\text{H}}\text{M}$  ( $n \sim 11$ ) (46.5 g).

[0072] NMR analysis yielded the following data:  $^1\text{H}$  NMR (in  $\text{CDCl}_3$ ): 4.70 ppm (broad, 1H, Si-H), 0.21 ppm~0.12 ppm (m, 4.7 H, Si- $\text{CH}_3$ ).  $^{29}\text{Si}$  NMR (in  $\text{CDCl}_3$ ): 8.87 ppm (m,  $\text{OSi}(\text{CH}_3)_3$ ), -36.31 ppm (m, Si-H).

[0073] Step 2: Incorporation of PEO side chains:

[0074] Tri(ethyleneglycol) monomethyl ether (Aldrich, 45.77 g, 0.279 mol),  $\text{MD}_n^{\text{H}}\text{M}$  ( $n \sim 11$ ) (21.93 g, 0.291 mol Si-H), and Tris(pentafluorophenyl)boron  $\text{B}(\text{C}_6\text{F}_5)_3$  (Aldrich, 0.101 g, 0.197 mmol) were used to afford the colorless liquid product designated Sample W169 (62.8 g). Referring to General formula II (as well as the final product in Fig. 1),  $n \sim 11$ .

[0075] Spectroscopic Data: IR showed no HO groups (at  $3300\sim3500\text{ cm}^{-1}$ ) and no Si-H (at  $2160\text{ cm}^{-1}$ ) present.  $^1\text{H}$  NMR (in  $\text{CDCl}_3$ ): 3.70~3.30 ppm (m, 12H,  $\text{CH}_2$ ), 3.15 ppm (s, 3H,  $\text{OCH}_3$ ), 0.05~0.10 ppm (m, 4.7 H, Si- $\text{CH}_3$ ).

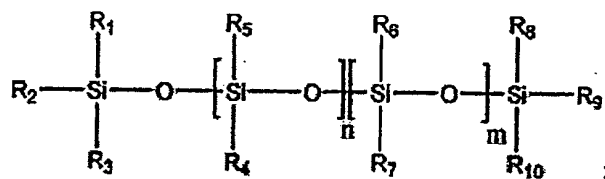
[0076] The specific implementations disclosed above are by way of example and for enabling persons skilled in the art to implement the invention only. We have made every effort to describe all the embodiments we have foreseen. There may be embodiments that are unforeseeable or which are insubstantially different. We have further made every effort to describe the invention, including the best mode of practicing it. Any omission of any variation of the invention disclosed is not intended to dedicate such variation to the public, and all unforeseen or insubstantial variations are intended to be covered by the claims appended hereto. Accordingly, the invention is not to be limited except by the appended claims and legal equivalents.

## CLAIMS

We claim:

1. A nonaqueous liquid type polymeric electrolyte comprising:

poly(siloxane-g-ethylene oxide) represented by the formula



wherein  $n = 4$  to  $20$ ,  $m = 0$  to  $20$ , and  $\text{R}_4$  is  $[-\text{O}-(\text{alkylene oxide})_k-\text{R}_{11}]$  wherein  $\text{R}_{11}$  is alkyl group; and

at least one ionizable salt.

2. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is equal to 4 to 12.
3. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is approximately equal to 8.
4. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $m$  is equal to 0 to 8.
5. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $m$  is approximately equal to 0.
6. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n = 4$  to 12 and  $m$  is approximately equal to 0.
7. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is approximately equal to 8 and  $m$  is approximately equal to 0.
8. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $\text{R}_1$ ,  $\text{R}_2$ ,  $\text{R}_3$ ,  $\text{R}_8$ ,  $\text{R}_9$  and  $\text{R}_{10}$  are chosen from the group consisting of: methyl, ethyl, propyl, and butyl.
9. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $\text{R}_5$ ,  $\text{R}_6$  and  $\text{R}_7$  are chosen from the group consisting of: methyl, ethyl, propyl and butyl.

10. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein said R<sub>4</sub> is poly(ethylene oxide) ether.
11. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein said poly(ethylene oxide) ether is methyl ether.
12. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein k is equal to 2 to 10.
13. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein k is approximately equal to 3.
14. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein said dissolved ionizable salt is an alkali metal salt.
15. The nonaqueous liquid type polymeric electrolyte recited in claim 14 wherein said alkali metal salt comprises a lithium salt.
16. The nonaqueous liquid type polymeric electrolyte recited in claim 14 wherein said salt comprises at least one salt selected from the group consisting of: LiN(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub> (LiTFSI), LiClO<sub>4</sub>, LiBF<sub>4</sub>, LiAsF<sub>6</sub>, LiPF<sub>6</sub>, LiCF<sub>3</sub>SO<sub>3</sub>, Li(CF<sub>3</sub>SO<sub>2</sub>)<sub>2</sub>N, LiC(CF<sub>3</sub>SO<sub>2</sub>)<sub>3</sub>, LiN(SO<sub>2</sub>C<sub>2</sub>F<sub>5</sub>)<sub>2</sub>, lithium bis(chelato) borate having five to seven membered rings, and lithium alkyl fluorophosphates.
17. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is 5:1 to 50:1.
18. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is about 10:1 to about 35:1.
19. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is 12:1 to 28:1.
20. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is about 15:1 to about 25:1.

21. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is about 15:1.
22. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein said ionizable salt comprises a quaternary ammonium salt having an anion selected from the following groups:  $\text{ClO}_4^-$ ,  $\text{BF}_4^-$ ,  $\text{AsF}_6^-$ ,  $\text{PF}_6^-$ ,  $\text{CF}_3\text{SO}_3^-$ ,  $(\text{CF}_3\text{SO}_2)_2\text{N}^-$ ,  $(\text{CF}_3\text{SO}_2)_3\text{C}^-$ ,  $(\text{C}_2\text{F}_5\text{SO}_2)_2\text{N}^-$ ,  $\text{PF}_3(\text{C}_2\text{F}_5)_3^-$ ,  $\text{PF}_3(\text{CF}_3)_3^-$ , and  $\text{B}(\text{C}_2\text{O}_4)_2^-$ .
23. The nonaqueous liquid type polymeric electrolyte recited in claim 1 further comprising boron detectable by at least one technique chosen from the following: mass spectroscopy, nuclear magnetic resonance (NMR), X-ray, and Fourier Transform Infrared Spectroscopy (FTIR).
24. An electrochemical storage device comprising said electrolyte recited in claim 1.
25. A medical device powered by at least one electrochemical storage device recited in claim 24.
26. A method for synthesizing a polyhydrosiloxane intermediary for preparing poly(siloxane-g-ethylene oxide), represented by the formula:
- $$\begin{array}{c} \text{R}_1 \\ | \\ \text{R}_2 - \text{Si} - \text{O} - \left[ \text{Si} - \text{O} \right]_n - \text{Si} - \text{R}_9 \\ | \quad | \quad | \\ \text{R}_3 \quad \text{R}_4 \quad \text{R}_{10} \end{array}$$
- wherein at least R4 or R5 is H,
- comprising the acts of:
- providing a precursor material;
- mixing with a chain-stopping compound in an amount sufficient to limit final chain lengths to n=4 to 20; and
- performing a ring-opening polymerization reaction.
27. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane.

28. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane with three to ten silicon-oxygen repeating units.

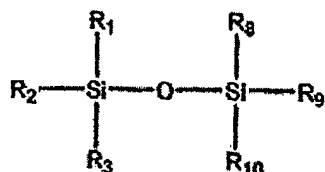
29. The method recited in claim 28 wherein said precursor comprises 1,3,5,7,9-pentamethylcyclopentasiloxane.

30. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane with three to five silicon-oxygen repeating units.

31. The method recited in claim 26 wherein said precursor comprises 1,3,5-trimethylcyclotrisiloxane.

32. The method recited in claim 26 wherein said precursor comprises 1,3,5,7-tetramethylcyclotetrasiloxane.

33. The method recited in claim 26 wherein said chain-stopping compound comprises a disiloxane represented by the formula:



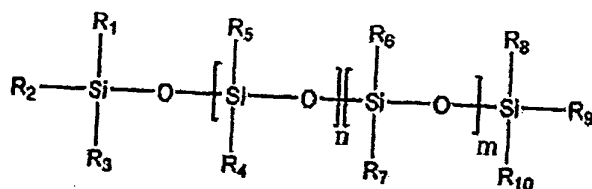
34. The method recited in claim 33 wherein R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>8</sub>, R<sub>9</sub>, and R<sub>10</sub> are chosen from the group consisting of: hydrogen, methyl, ethyl, propyl, and butyl.

35. The method recited in claim 26 wherein said chain-stopping compound comprises hexamethyldisiloxane (HMDS).

36. The method recited in claim 26 wherein said ring opening polymerization comprises the act of adding a chain stopping compound in the presence of sulfuric acid.

37. The method recited in claim 26 wherein said ring opening polymerization comprises the act of adding hexamethyldisiloxane in the presence of sulfuric acid.

38. A method for synthesizing a polysiloxane electrolyte comprising the acts of:  
providing a polyhydrosiloxane intermediary represented by the formula:



wherein  $n=4$  to 20 and at least  $R_4$ ,  $R_5$ ,  $R_6$ , or  $R_7$  comprises hydrogen;

mixing with a hydroxyl compound;

adding a dehydrocoupling catalyst;

flushing with inert gas;

adding a solvent;

heating the resulting mixture;

stirring;

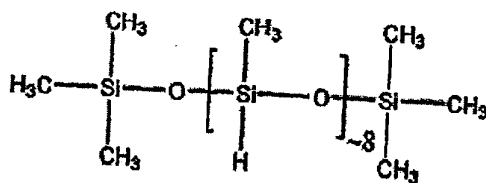
drying in a vacuum; and

doping with at least one lithium salt.

39. The method recited in claim 38 wherein said  $m=0$ .

40. The method recited in claim 38 wherein said R groups that are not hydrogen are methyl groups.

41. The method recited in claim 38 wherein said polyhydrosiloxane intermediary comprises a structure represented by the formula:



42. The method recited in claim 38 wherein said dehydrocoupling catalyst contains boron.

43. The method recited in claim 38 wherein said dehydrocoupling catalyst comprises tris(pentafluorophenyl)boron ( $B(C_6F_5)_3$ ).

44. The method recited in claim 38 wherein said dehydrocoupling catalyst is loaded as a percentage of the moles of Si-H groups present in the substrates.
45. The catalyst loading of claim 44 wherein said loading percentage is 0.01% to 10.00% on a per mole basis.
46. The catalyst loading of claim 44 wherein said loading percentage is 0.01% to 2.00% on a per mole basis.
47. The catalyst loading of claim 44 wherein said loading percentage is approximately equal to 0.05% on a per mole basis.
48. The method recited in claim 38 wherein said hydroxyl compound comprises a substituted methyl alcohol.
49. The method recited in claim 38 wherein said hydroxyl compound comprises a poly(ethylene glycol) ether.
50. The method recited in claim 38 wherein said hydroxyl compound comprises a poly(ethylene glycol) monomethyl ether.
51. The method recited in claim 38 wherein said hydroxyl compound comprises tri(ethylene glycol) monomethyl ether.
52. The method recited in claim 38 wherein said polyhydrosiloxane contains 4 to 20 siloxane repeating units.
53. The method recited in claim 38 wherein said inert gas is chosen from the group consisting of: argon, nitrogen, and mixtures thereof.
54. The method recited in claim 38 wherein said inert gas is anhydrous.
55. The method recited in claim 38 wherein said solvent is toluene.
56. The method recited in claim 38, wherein said solvent is benzene.
57. The method recited in claim 38 wherein said heating of said resulting mixture is to a range between 40 and 200°C.

58. The method recited in claim 38 wherein said heating of said resulting mixture is to about 70 to 75°C.

59. The method recited in claim 38 wherein said at least one lithium salt is selected from the group consisting of:  $\text{LiN}(\text{SO}_2\text{CF}_3)_2$  (LiTFSI),  $\text{LiClO}_4$ ,  $\text{LiBF}_4$ ,  $\text{LiAsF}_6$ ,  $\text{LiPF}_6$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ ,  $\text{LiC}(\text{CF}_3\text{SO}_2)_3$ ,  $\text{LiN}(\text{SO}_2\text{C}_2\text{F}_5)_2$ , bis(chelato) borate having five to seven membered rings, lithium alkyl fluorophosphates, and mixtures thereof.

60. A method for synthesizing poly(siloxane-g-3 ethylene oxide) (n~8) comprising the acts of:

- providing precursor 1,3,5,7-tetramethylcyclotetrasiloxane ( $\text{D}_4^{\text{H}}$ );
- providing a chain stopping compound hexamethyldisiloxane (HMDS);
- performing a ring opening polymerization reaction;
- adding HMDS (in a 1:2 molar ratio) in the presence of concentrated sulfuric acid;
- stirring;
- bringing mixture to room temperature;
- washing;
- dissolving in solvent;
- removing the solvent;
- mixing with an ethyleneglycol monomethyl ether; and
- adding a dehydrocoupling catalyst.

61. The method recited in claim 60 wherein said dehydrocoupling catalyst comprises tris(pentafluorophenyl)boron  $\text{B}(\text{C}_6\text{F}_5)_3$ .

62. The method recited in claim 60 further comprising the act of doping with at least one alkali metal salt.

63. The method recited in claim 62 wherein said alkali metal salt comprises a lithium salt.

64. The method recited in claim 63 wherein at least one lithium salt is selected from the group consisting of:  $\text{LiN}(\text{SO}_2\text{CF}_3)_2$  (LiTFSI),  $\text{LiClO}_4$ ,  $\text{LiBF}_4$ ,  $\text{LiAsF}_6$ ,  $\text{LiPF}_6$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ ,  $\text{LiC}(\text{CF}_3\text{SO}_2)_3$ ,  $\text{LiN}(\text{SO}_2\text{C}_2\text{F}_5)_2$ , bis(chelato) borate having five to seven membered rings, lithium alkyl fluorophosphates, and mixtures thereof.

65. A nonaqueous electrolyte made by the process of claim 60.

66. An electrochemical storage device comprising said electrolyte recited in claim 65.

67. A medical device powered by at least one electrochemical storage device recited in claim 66.

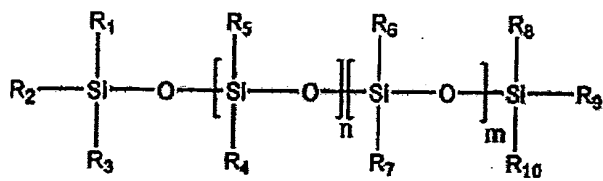
## AMENDED CLAIMS

[Received by the International Bureau on 05 August 2003 (05.08.03):  
original claims 1-43 amended; remaining claims unchanged; (5 pages)]

We claim:

1. A nonaqueous liquid type polymeric electrolyte comprising:

poly(siloxane-g-ethylene oxide) represented by the formula



wherein  $n = 4$  to  $20$ ,  $m = 0$  to  $20$ , and  $\text{R}_4$  is  $[-\text{O}-(\text{alkylene oxide})_k-\text{R}_{11}]$  wherein  $\text{R}_{11}$  is alkyl group; and

at least one ionizable salt.

2. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is equal to 4 to 12.
3. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is approximately equal to 8.
4. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $m$  is equal to 0 to 8.
5. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $m$  is approximately equal to 0.
6. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n = 4$  to  $12$  and  $m$  is approximately equal to 0.
7. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $n$  is approximately equal to 8 and  $m$  is approximately equal to 0.
8. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $\text{R}_1$ ,  $\text{R}_2$ ,  $\text{R}_3$ ,  $\text{R}_8$ ,  $\text{R}_9$  and  $\text{R}_{10}$  are chosen from the group consisting of: methyl, ethyl, propyl, and butyl.
9. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein  $\text{R}_5$ ,  $\text{R}_6$ , and  $\text{R}_7$  are chosen from the group consisting of: methyl, ethyl, propyl and butyl.

10. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein said R<sub>4</sub> is poly(ethylene oxide) ether.

11. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein said poly(ethylene oxide) ether is methyl ether.

5 12. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein k is equal to 2 to 10.

13. The nonaqueous liquid type polymeric electrolyte of claim 10 wherein k is approximately equal to 3.

14. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein said  
10 dissolved ionizable salt is an alkali metal salt.

15. The nonaqueous liquid type polymeric electrolyte recited in claim 14 wherein said alkali metal salt comprises a lithium salt.

16. The nonaqueous liquid type polymeric electrolyte recited in claim 14 wherein said salt comprises at least one salt selected from the group consisting of: LiN(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub> (LiTFSI),  
15 LiClO<sub>4</sub>, LiBF<sub>4</sub>, LiAsF<sub>6</sub>, LiPF<sub>6</sub>, LiCF<sub>3</sub>SO<sub>3</sub>, Li(CF<sub>3</sub>SO<sub>2</sub>)<sub>2</sub>N, LiC(CF<sub>3</sub>SO<sub>2</sub>)<sub>3</sub>, LiN(SO<sub>2</sub>C<sub>2</sub>F<sub>5</sub>)<sub>2</sub>, lithium bis(chelato) borate having five to seven membered rings, and lithium alkyl fluorophosphates.

17. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is 5:1 to 50:1.

20 18. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is about 10:1 to about 35:1.

19. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is 12:1 to 28:1.

20. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side  
25 chain oxygen vs. lithium ratio is about 15:1 to about 25:1.

21. The nonaqueous liquid type polymeric electrolyte recited in claim 1 wherein the side chain oxygen vs. lithium ratio is about 15:1.

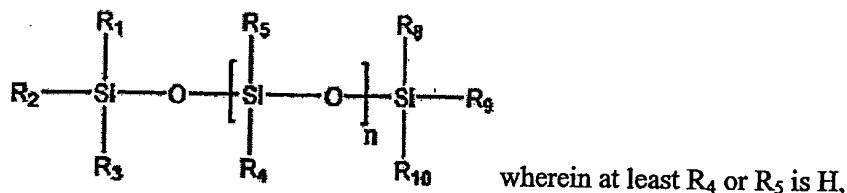
22. The nonaqueous liquid type polymeric electrolyte of claim 1 wherein said ionizable salt comprises a quaternary ammonium salt having an anion selected from the group consisting of:  $\text{ClO}_4^-$ ,  $\text{BF}_4^-$ ,  $\text{AsF}_6^-$ ,  $\text{PF}_6^-$ ,  $\text{CF}_3\text{SO}_3^-$ ,  $(\text{CF}_3\text{SO}_2)_2\text{N}^-$ ,  $(\text{CF}_3\text{SO}_2)_3\text{C}^-$ ,  $(\text{C}_2\text{F}_5\text{SO}_2)_2\text{N}^-$ ,  $\text{PF}_3(\text{C}_2\text{F}_5)_3^-$ ,  $\text{PF}_3(\text{CF}_3)_3^-$ , and  $\text{B}(\text{C}_2\text{O}_4)_2^-$ .

23. The nonaqueous liquid type polymeric electrolyte recited in claim 1 further comprising boron detectable by at least one technique chosen from the following: mass spectroscopy, nuclear magnetic resonance (NMR), X-ray, and Fourier Transform Infrared Spectroscopy (FTIR).

24. An electrochemical storage device comprising said electrolyte recited in claim 1.

25. A medical device powered by at least one electrochemical storage device recited in claim 24.

26. A method for synthesizing a polyhydrosiloxane intermediary for preparing poly(siloxane-g-ethylene oxide), represented by the formula:



comprising the acts of:

providing a precursor material;

mixing with a chain-stopping compound in an amount sufficient to limit final chain lengths to  $n=4$  to 20; and

performing a ring-opening polymerization reaction.

27. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane.

28. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane with three to ten silicon-oxygen repeating units.

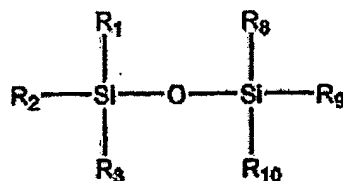
29. The method recited in claim 28 wherein said precursor comprises 1,3,5,7,9-pentamethylcyclopentasiloxane.

5 30. The method recited in claim 26 wherein said precursor comprises a cyclic polysiloxane with three to five silicon-oxygen repeating units.

31. The method recited in claim 26 wherein said precursor comprises 1,3,5-trimethylcyclotrisiloxane.

32. The method recited in claim 26 wherein said precursor comprises  
10 1,3,5,7-tetramethylcyclotetrasiloxane.

33. The method recited in claim 26 wherein said chain-stopping compound comprises a disiloxane represented by the formula:



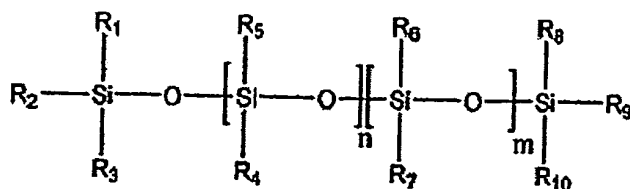
34. The method recited in claim 33 wherein  $R_1$ ,  $R_2$ ,  $R_3$ ,  $R_8$ ,  $R_9$ , and  $R_{10}$  are chosen from  
15 the group consisting of: hydrogen, methyl, ethyl, propyl, and butyl.

35. The method recited in claim 26 wherein said chain-stopping compound comprises hexamethyldisiloxane (HMDS).

36. The method recited in claim 26 wherein said ring opening polymerization comprises the act of adding a chain stopping compound in the presence of sulfuric acid.

20 37. The method recited in claim 26 wherein said ring opening polymerization comprises the act of adding hexamethyldisiloxane in the presence of sulfuric acid.

38. A method for synthesizing a polysiloxane electrolyte comprising the acts of:  
providing a polyhydrosiloxane intermediary represented by the formula:



wherein  $n=4$  to  $20$  and at least  $R_4$ ,  $R_5$ ,  $R_6$ , or  $R_7$  comprises hydrogen;

mixing with a hydroxyl compound;

adding a dehydrocoupling catalyst;

5 flushing with inert gas;

adding a solvent;

heating the resulting mixture;

stirring;

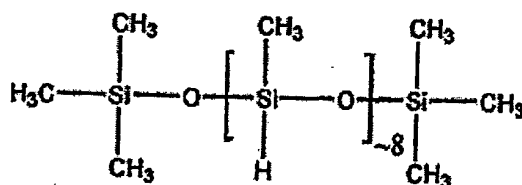
drying in a vacuum; and

10 doping with at least one lithium salt.

39. The method recited in claim 38 wherein said  $m=0$ .

40. The method recited in claim 38 wherein said R groups that are not hydrogen are methyl groups.

41. The method recited in claim 38 wherein said polyhydrosiloxane intermediary  
 15 comprises a structure represented by the formula:



42. The method recited in claim 38 wherein said dehydrocoupling catalyst contains boron.

43. The method recited in claim 38 wherein said dehydrocoupling catalyst comprises  
 20 tris(pentafluorophenyl)boron ( $B(C_6F_5)_3$ ).

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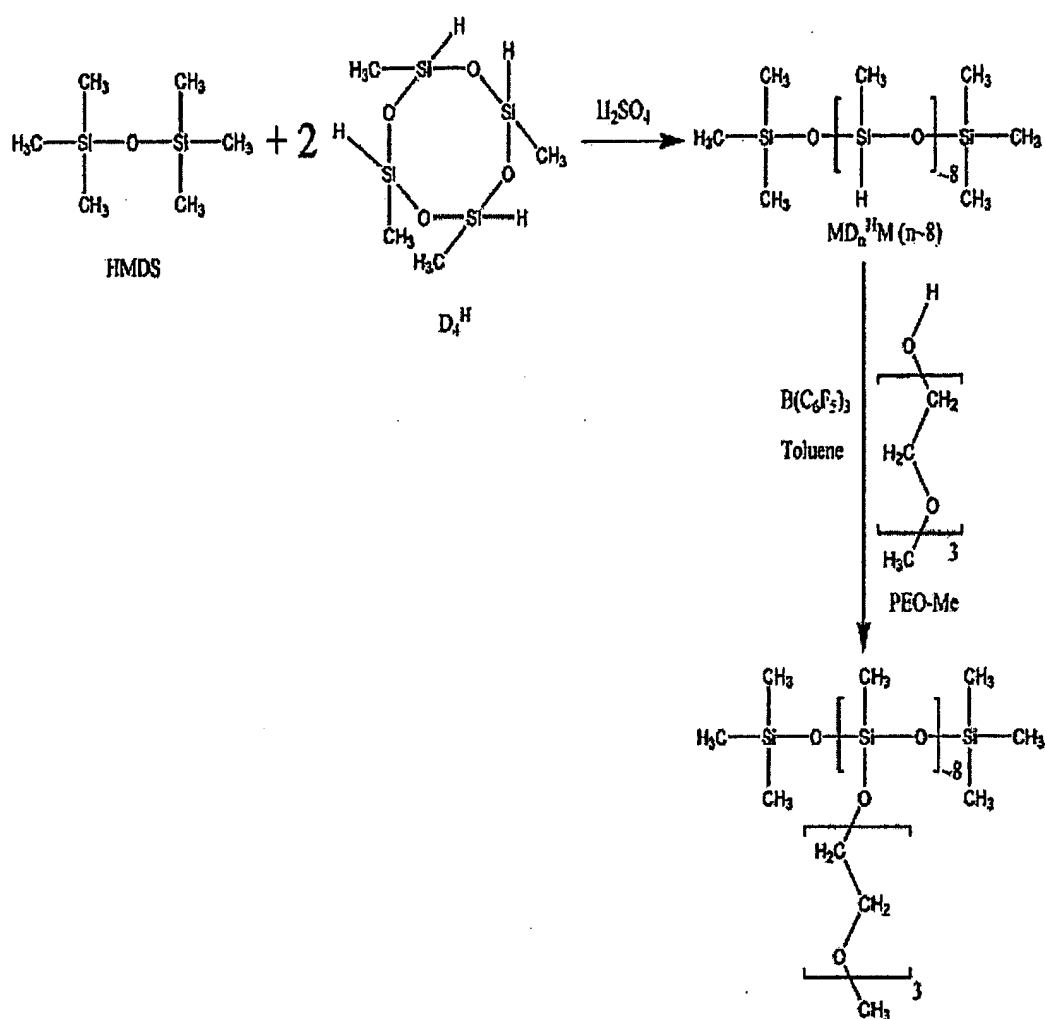


Fig. 1

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## W100 Conductivity Data

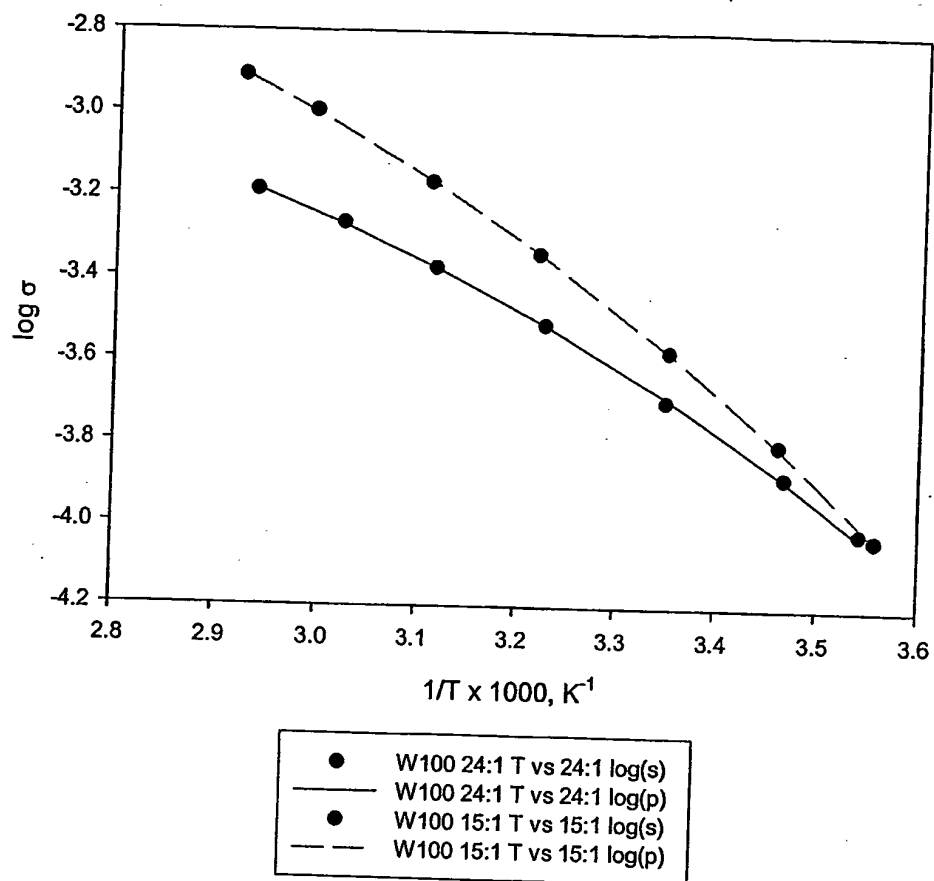


Fig. 2

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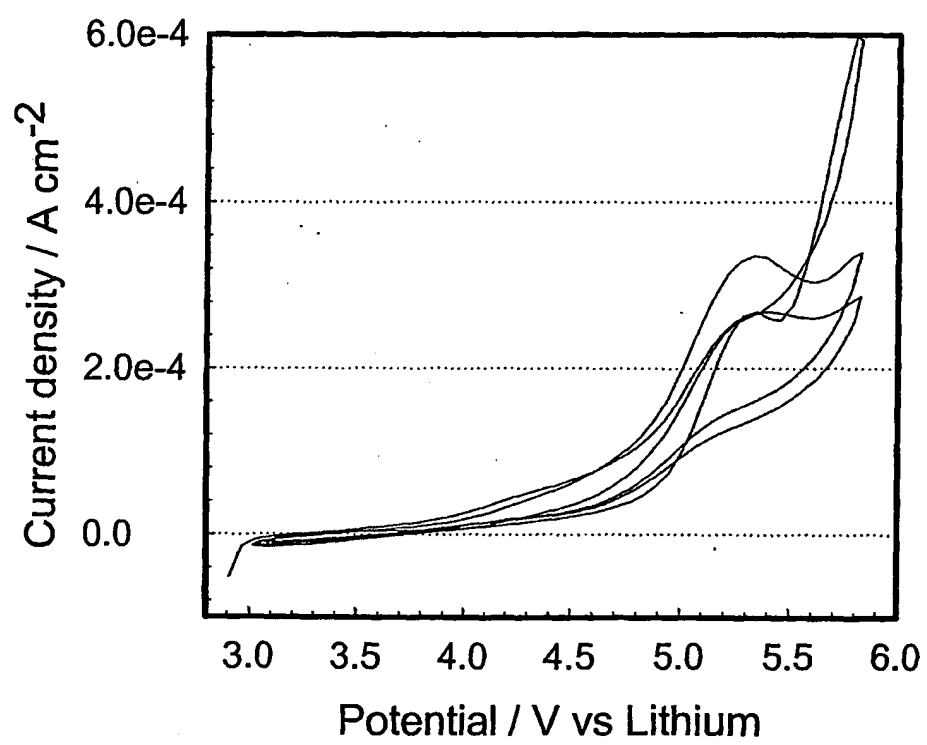
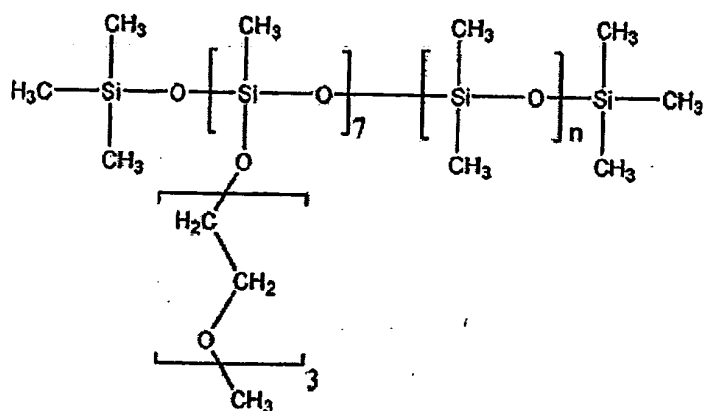


Fig. 3

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Sample W76 (n=6.3)

Fig. 4A

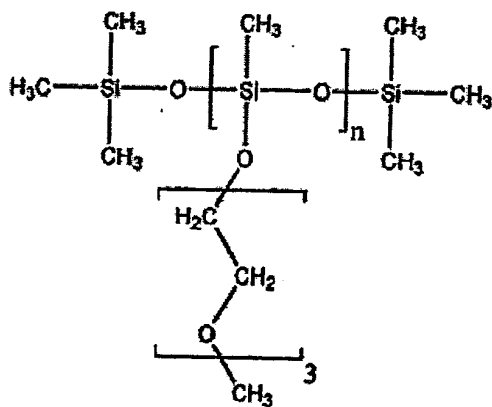
Sample W22P (n = 32 - 38; K<sub>2</sub>CO<sub>3</sub>, catalyst)Sample W102 (n = 33-35; B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> catalyst)

Fig. 4B

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Conductivity at various LiTFSI compositions @ 25°C

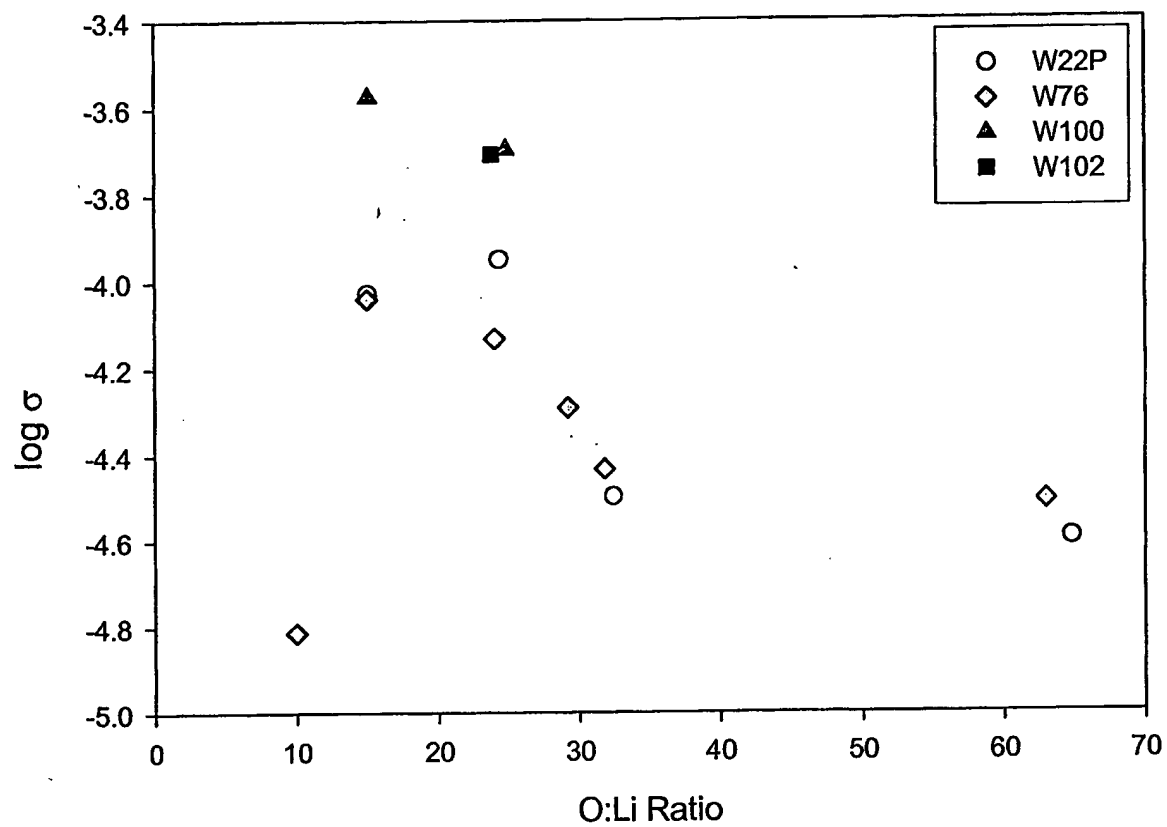


Fig. 5

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## VTF Conductivity of W22P, W100, and W102 (variable LiTFSI)

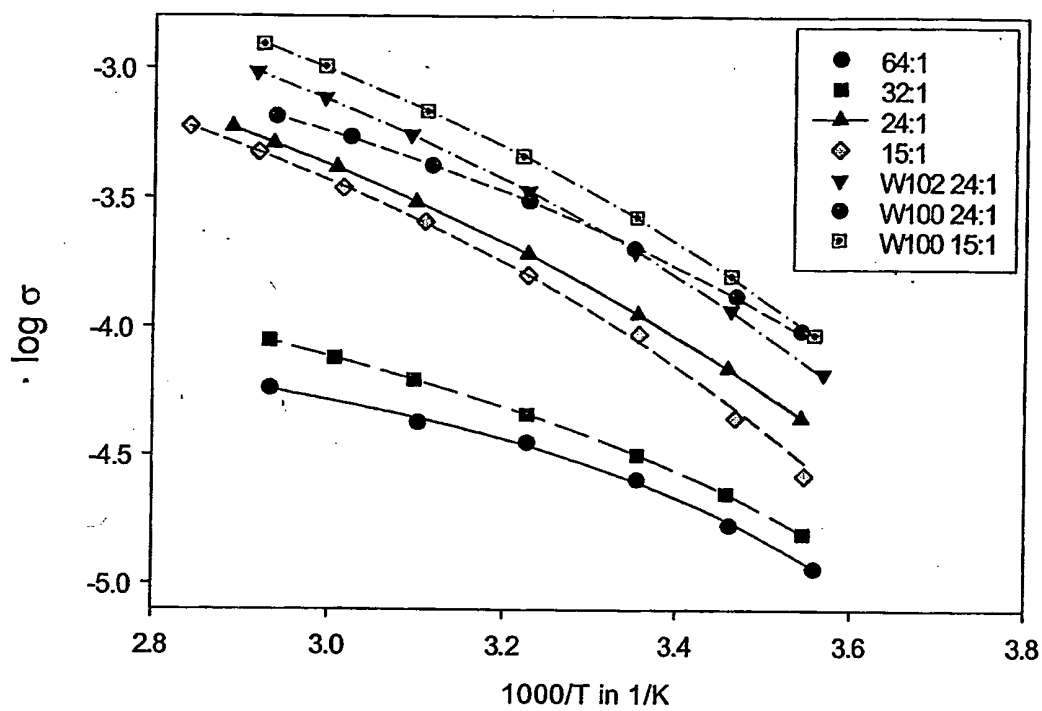


Fig. 6

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/08740

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(7) : H01M 6/14, 6/18, 10/40; H01G 9/025

US CL : 252/62.2; 429/188, 302-304, 313, 333, 321-323; 361/504, 505, 523

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 252/62.2; 429/188, 302-304, 313, 333, 321-323; 361/504, 505, 523

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category * | Citation of document, with indication, where appropriate, of the relevant passages                         | Relevant to claim No. |
|------------|--|-----------------------|
| X          | US 5,885,733 A (OHSAWA et al) 23 March 1999 (23.03.1999), see col. 2, lines 12-62 and col. 4, lines 19-29. | 1-25                  |
| —          |  | -----                 |
| Y          |  | 26-67                 |
| Y          | US 5,112,512 A (NAKAMURA) 12 May 1992 (12.05.1992), see abstract and col. 3-col. 7.                        | 1-67                  |
| A          | US 5,419,984 A (CHALONER-GILL et al) 30 May 1995 (30.05.1995).   | 1-67                  |
| A          | US 5,690,702 A (SKOTHEIM et al) 25 November 1997 (25.11.1997).   | 1-67                  |
| A          | US 6,124,062 A (HORIE et al) 26 September 2000 (26.09.2000).   | 1-67                  |

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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| "E" earlier application or patent published on or after the international filing date   | "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone   |
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Date of the actual completion of the international search

12 June 2003 (12.06.2003)

Date of mailing of the international search report

11 JUL 2003

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